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difficult. Most of the industrial applications involve hole making in these materials. Bellows and Kohls [1] reported various non-traditional machining methods that can be used to solve the modern hole making problems. They reported detailed overview of various non- traditional machining processes, including their capabilities. They suggested guidelines for selecting a particular process. They also reported the cost and drilling capability comparisons of various processes, Fig 1.3 (a) and (b). It is evident from the fig 1.3 (a) that for micro hole drilling in aerospace materials with large aspect ratios, conventional drilling is expensive compared to unconventional processes, and the aspect ratios that can be achieved with conventional processes is less. LBM costs low for very fine hole drilling. For lower aspect ratios the cost of EDM, STEM, and ES remains the same, but for higher aspect ratio requirements their cost increases steeply. Fig 1.3 (b) shows a comparison of the range of hole sizes found to be practical for production applications by ES, STEM, and LBM. They also reported the selection of electrolyte in ESD for machining a specific kind of workpiece material.

Jain [2] has studied the electro chemical drilling process using bare, coated and bit type electrodes . He found that the use of tool bits in drilling operation can result into a substantial reduction in power consumption and overcut. Tool bits with insulated sides and low operating voltages lead to practically zero over cut. He performed electro-chemical drilling (ECD) experiments using $NaCl$ electrolyte to study the effect of voltage on anode profile, and the effect of tool diameter on over cut. Using finite element technique (FET), anodic profiles for different cases have been obtained and a comparison has been made between experimental and analytical anodic profiles. He also found that the electro-chemically drilled holes have the shape of an elongated s ($\int$).

Sreejith et al [3] reported experimental findings concerning the effects of process parameters on the profile of a spike obtained during electro-chemical drilling of a blind hole in HSS workpiece. They concluded that the spike volume is largely governed by the feed rate, hole diameter, and taper angle. The effect of applied voltage on spike volume was not significant.

corrosive to acids.The pump selected for ESD has the following specifications,

Head :	3 meters
Drive :	0.25 kw
Phase :	Single phase
speed :	2850 rpm
Make :	UP National MFRS pvt.Ltd

Piping

The pipes carrying the electrolyte must be acid resistant. In ESD, the pipes used are of soft PVC material. Pipes are clamped at the junctions by wire clamping to avoid the release of pipes due to electrolyte pressure. The pipes used in the flow path are of 0.125 m diameter.

2.4 Power supply

The ESD process needs a high voltage and low current power supply. The voltage required in ESD are 10 to 15 times more than that of the ECM. The 3-phase 440 V A.C. power supply available from the mains is converted to D.C. voltage by a step-down transformer and rectifier. In ESD, the current drawn during the machining is of the order of millie amperes that is very low. So a D.C. digital multi-meter is connected in series in the circuit to measure the current during machining. It employs a 9 V D.C. battery for its working. Specifications of the power supply unit used in ESD are as follows.

A.E Constant current rectifier

Input voltage	230 V
Output voltage	0-150 V
Phase	1 phase
Output current	20+ 0.5 A
Capacity	3.9 kVA

$s.no$	x_0	x_1	x_2	x_1^2	x_2^2	x_1x_2
1	1	-1	-1	1	1	1
2	1	1	-1	1	1	-1
3	1	-1	1	1	1	-1
4	1	1	1	1	1	1
5	1	-1.414	0	2	0	0
6	1	1.414	0	2	0	0
7	1	0	-1.414	0	2	0
8	1	0	1.414	0	2	0
9	1	0	0	0	0	0
10	1	0	0	0	0	0
11	1	0	0	0	0	0
12	1	0	0	0	0	0
13	1	0	0	0	0	0

Table 2.2: Central composite rotatable design for two factors [13]

x	*voltage* (V)	*concentration* (%C)
-1,414	50	5
-1	65	8
0	100	15
1	135	22
1.414	150	25

Table 2.3: Values of parameters for different levels

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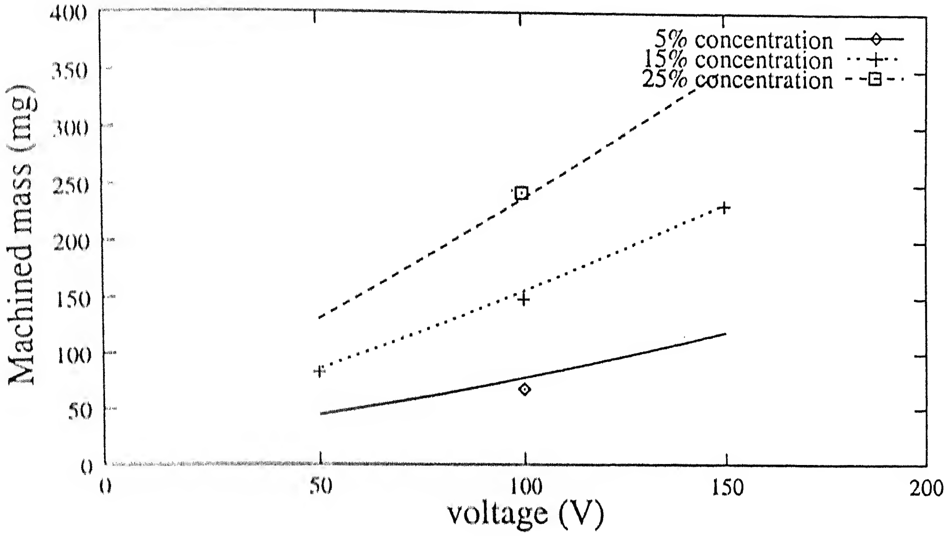

Figure 3.5: Effect of supply voltage on machined mass
for different electrolyte concentrations

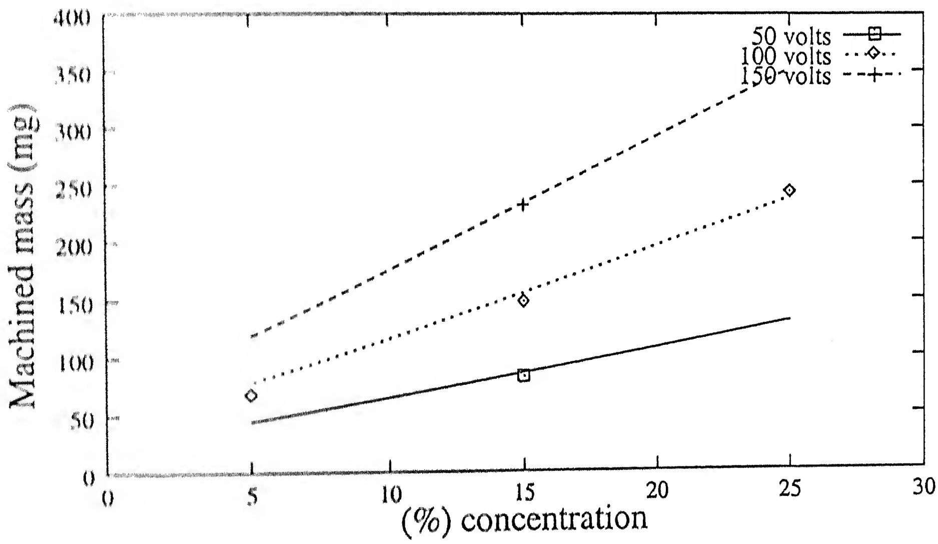

Figure 3.6: Effect of electrolyte concentration on machined mass
for different voltages

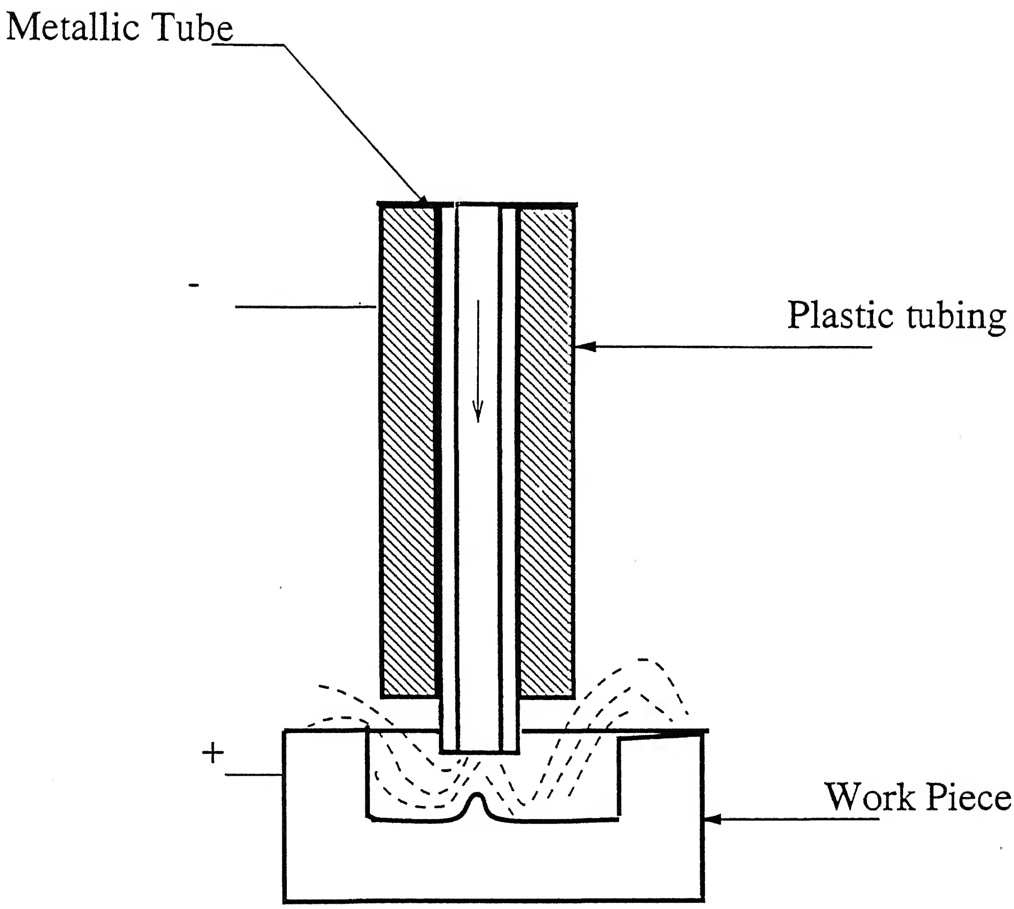

Figure 4.1: Schematic diagram of STEM process

Certificate

This is to certify that the work contained in the thesis entitled "***Electro-stream drilling of high speed steel***", by ***D. Sridhar Sastry***, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

(Dr. R. Shekhar)
Associate Professor,
Department of MME,
Indian Institute of Technology,
Kanpur, 208016, India.

(Dr. V. K. Jain)
Professor,
Department of Mechanical Engg,
Indian Institute of Technology,
Kanpur, 208016, India.

July, 1999

Acknowledgement

I take this opportunity to express the feeling of sincere gratitude towards my thesis supervisors **Dr. V. K. Jain and Dr. R. Shekhar** for their expert guidance and encouragement which have been the vital factors in successful completion of the present work.

I am thankful to the staff of manufacturing Science Laboratory, Mr. R. M. Jha, Mr. H. P. Sharma, Mr. Namdev for their consistent efforts in making the experimental set up. I am specially thankful to Mr. Anil for his cooperation in fabricating the set-up, and his timely help during experimentation.

I am extremely thankful to the staff of central glass blowing people for their help in fabricating the glass nozzle.

I am very much thankful to Mr. N. K. Jain and Mr. Vinod Yadav for their constant encouragement and suggestions in writing the thesis.

I would like to express my thanks to all who have helped me, specifically Mr. Lal of ACMS.

It is indeed my great pleasure to express my sincere thanks to Gayatri Prasad, Seshu, Prabhudas, Janardhan Reddy, Venu , Phani and all my friends for their timely help and friendly cooperation in sorting out my problems and making my stay at I.I.T., Kanpur, a pleasant and memorable one. I am very much grateful to my parents who always supported me despite many problems in all the circumstances.

(D. Sridhar Sastry)

Abstract

Advances in the field of aerospace, gas turbine, nuclear technologies have produced the need to machine the super alloys and refractory metals. The complex characteristics of these materials posed machining problems which are beyond the capabilities of conventional machining processes. One such problem is drilling small deep holes in the super alloys. Electro stream drilling (ESD) was found to be a potential process for drilling micro holes in these materials. Basic ESD process details were reported by previous researchers. So far, parametric study reported involved the usage of salt electrolytes only. In the present work acidic electrolyte (HCl) is employed for machining of the work material. For this purpose experimental electro stream drilling machine has been designed and fabricated. Experiments have been performed with high speed steel (HSS) as work material. Few experiments are also conducted on Inconel super alloy. During the course of study an attempt has been made to evaluate the effect of process parameters (i.e applied voltage and electrolyte concentration) on ESD process performance. Geometrical aspects such as machined hole profile, hole taper have also been studied. SEM photographs of the ESD machined holes are also presented.

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Chapter 1

Introduction

1.1 Introduction

Machining has always played an important role in shaping not only materials but in fact the fate of humanity. This is so because machining has a special status in the whole spectrum of all manufacturing processes .

Traditionally shaping of components by selective removal of material has been performed by mechanically operated tools, the inherent principle being that a hard material will cut a softer one . The more familiar machining operations include turning, boring, milling, planing, broaching and grinding .

Recent advances in science and technology, especially in areas such as nuclear and aerospace engineering have imposed a severe demand on the materials requirements. This aspect led to the development of high strength and temperature resistant, hard and brittle materials, whose machining posed serious problems to the manufacturing industries. Processes for machining such hard and brittle materials are grouped under the common name of $Unconventional\ machining$ or $Non - traditional\ machining$ processes.

To meet the demand originating owing to the advances in the jet engine technology, machining of the super alloys and refractory metals has become essential. The complex designs associated with the jet engine hardware have posed

machining problems which are beyond the capabilities of conventional machining processes. One such problem is drilling small deep holes in the super alloys. Problems such as tool wear and excessive heat generation at the tool and workpiece interface are encountered while employing conventional mechanical drilling techniques. Additionally, there is some obstruction to the coolant flow since the chip direction is opposite to the direction of drill penetration. It is also considerably difficult to drill holes smaller than 250 micrometer by conventional mechanical drilling. Rigidity requirements for the tool is another major problem in conventional drilling of small and deep holes. In such cases, non-traditional machining (or advanced) processes are particularly adaptable for economic hole making. Several other situations that favour the application of these advanced machining processes (AMPs) for drilling are:

- workpiece made of difficult to machine material,
- drilling with shallow entry angles,
- drilling of non-circular shapes,
- micro hole drilling,
- drilling with large aspect ratios.

Various non-traditional machining methods used for drilling micro holes are electrochemical machining (ECM), electric discharge machining (EDM), laser beam machining (LBM), and electron beam machining (EBM). EDM and LBM are thermal processes and therefore cause the formation of heat affected zones and micro cracks on the work surface, resulting in metallurgical damage of the workpiece surface material. EBM, LBM have limited applications due to their higher cost. Table 1.1 shows a comparison of various non-traditional hole making processes. The table shows that EBM, LBM can be used for machining any kind of materials, whereas EDM, ECM, STEM, and ES can be used only to machine electrically conducting materials. Typical minimum diameter can be achieved by LBM.

Process	EDM	ECM	STEM	ES	LBM
Types of material	conductive	conductive	conductive	conductive	Any
Hole size (d) in Typical Max practical	0.005-0.25 0.000,35 0.25	0.25 and up 0.125 3	0.03-0.1 0.020 0.25	0.005-0.035 0.002 0.04	0.005-0.050 0.000,75 0.06
Aspect ratio (l:d) Typical maximum	10:1 20:1	8:1 20:1	16:1 300:1	16:1 40:1	16:1 75:1
Special attributes	Irregular contours no burrs delicate components	contoured and irregular shapes; no burrs	shaped and; multiangled no burrs	High integrity; no burrs	Rapidly adjustable

Table 1.1: Comparison of various non-traditional hole making processes [1]

STEM process gives the max machined depth. STEM and ES are more suitable for drilling micro holes with large aspect ratios.

ECM is considered as an efficient process for machining complicated shapes in any hard and electrically conductive material. The situations that make ECM a prime candidate for machining are as given below.

- Work material is hard or tough enough.
- Difficult contours are involved .
- Machining without cold working is needed.
- Repetitive production is involved.
- Distortion less, burr-free surfaces are required.
- High surface quality is required.

But drilling of small holes with large aspect ratios is beyond the scope of ECM because of over cutting on account of sideway current flow . Another problem is the formation of insoluble precipitates during machining which inhibits the machining of small deep holes. This aspect led to the development of specialized EC drilling techniques, the prominent micro drilling techniques being shaped tube electrolytic machining (STEM), and electro stream drilling (ESD).

Shaped tube electrolytic machining is a specialized ECM technique for drilling small, deep holes utilizing acid electrolytes. In STEM, electrode is a carefully straightened acid-resistant metal tube coated with a film of enamel type insulation. The electrode can be shaped to drill odd cross sections. The voltage used in the process is of the order of 5-15 V. Holes of 0.5-6.4 mm diameter with aspect ratio of the order of 300:1 can be achieved.

Electro stream drilling was first developed in the mid-1960s by the General Electric Company, Aircraft Engine Group.

Working Principle of ESD

ESD employs a negatively charged high velocity stream of acidic electrolyte to achieve anodic dissolution of workpiece material. A thin, electrically charged electrolytic stream is obtained by pumping electrolyte through a specially drawn non-conducting nozzle (glass nozzle) of fine outlet diameter. A Platinum wire inserted in nozzle acts as cathode while work piece is made anode. Platinum is used because of its good electrical conductivity, and its inertness to acidic action. As the charged electrolytic stream impinges on the work piece, material is removed through electrolytic dissolution and is flushed out from the interaction area in the form of metal ions in the solution. Fig 1.1 depicts the schematic diagram of the ESD process. The acidic electrolytes used in ESD dissolves the precipitates thereby avoiding sludge formation during drilling. The electro chemical reactions which might occur when machining iron with approximately zero pH hydro chloric acid solution are given below.

at anode

$$Fe \rightarrow Fe^{2+} + 2e$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e$$

$$2Cl^- \rightarrow Cl_2 + 2e$$

at cathode

$$2H^+ + 2e \rightarrow H_2$$

$$Fe^{2+} + 2e \rightarrow Fe$$

In ESD , voltages of the order of 10-15 times that of ECM (5-30 V) are employed. This high voltage requirement in ESD is due to the large gap between platinum wire tip, and work piece material. As a result high voltages are essential to overcome the ohmic resistance due to this gap for machining to takes place. With ESD holes as small as 0.127 mm diameter can be drilled. Insertion of a nozzle with a formed tip permits right angled drilling deep inside the prior hole Fig 1.2. The potential applications of ESD are in fuel injector nozzles of diesel engines, viscosity meters, watches, gas turbine vanes, etc.

1.2 Literature survey

Controlled dissolution of anodic electrode, during electrolysis, is the basis of electro chemical machining. The general principle of material removal by anodic dissolution was one of the discoveries of Michael Faraday. Faraday in 1833 established the laws of electrolysis. From Faraday's work stemmed the development of electro plating, electro polishing, and electro chemical machining, which are the processes well established in manufacturing industries. Suggestions for the application of metal removal as a metal working technique were proposed by W. Gussef, a Russian scientist, in 1929 and much latter by C. F. Burgess in a paper for the electro chemical society in 1941 .

To meet the demands of technologically advanced industries like aeronautic, nuclear, gas-turbine , automobile, rapid developments have taken place in the field of material science to develope the materials having better properties in terms of strength, hardness, and toughness at elevated temperatures. It has resulted in high strength temperature resistant (HSTR) alloys, advanced ceramics and fiber reinforced plastics (FRP). Shaping of these materials by traditional methods is

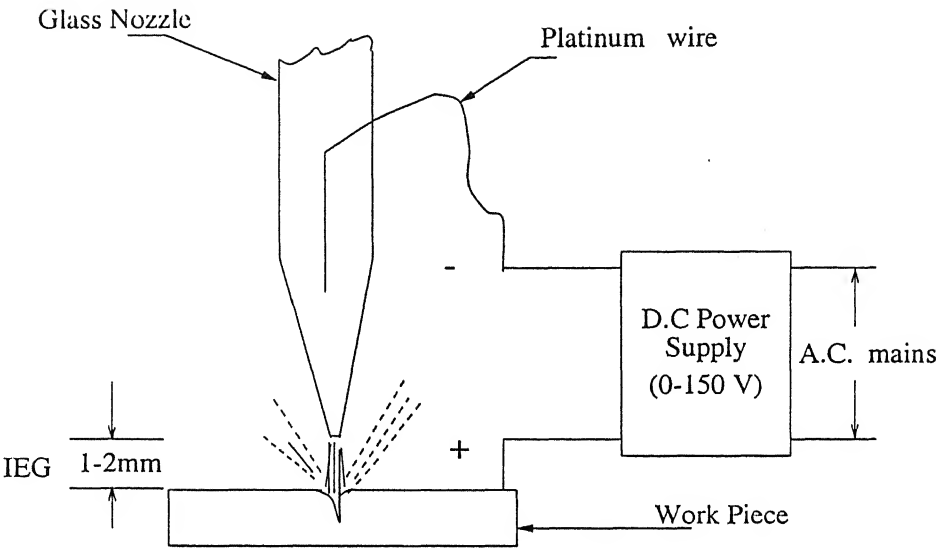

Figure 1.1: Schematic diagram of ESD process

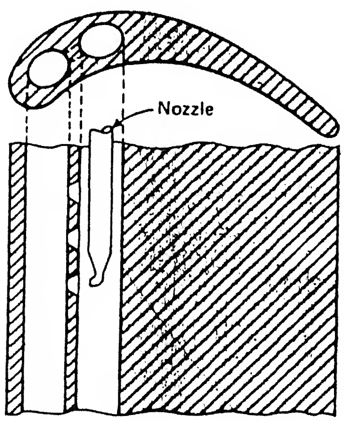

Figure 1.2: ES drilling of cross holes deep within workpiece [1]

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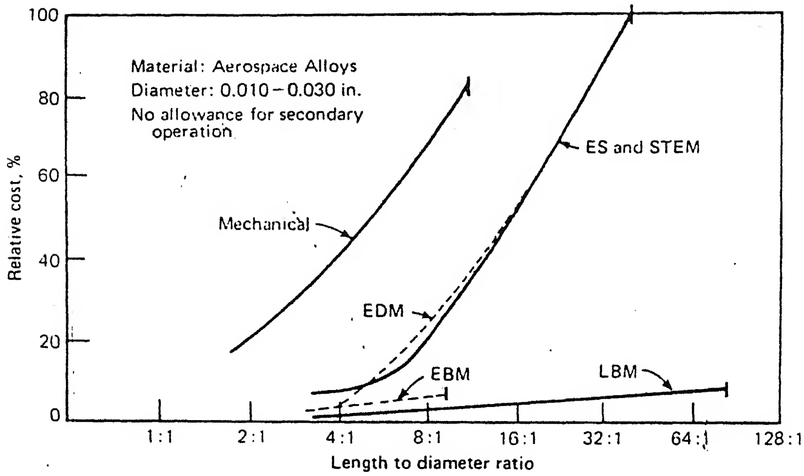
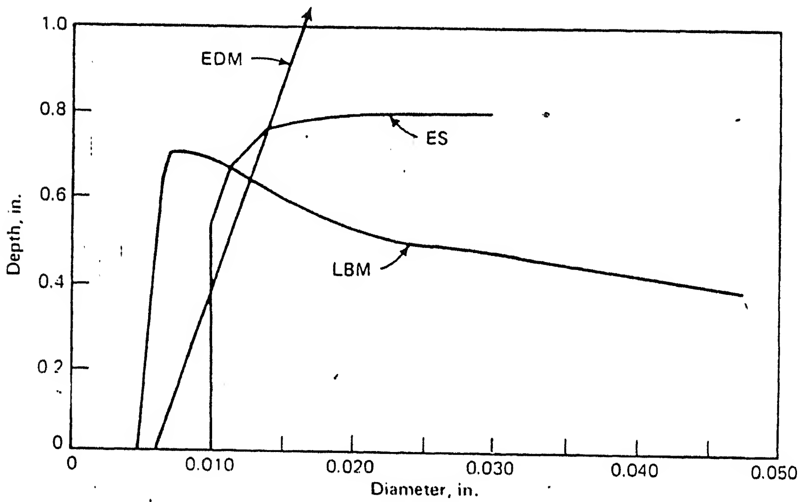
Electro-chemical hole making with insulated tools and active (non passivating) electrolytes would always show a tendency for etching and irregular machining along the hole sides. Chryssoluris and Wollowitz [4] developed an electro chemical hole making technique which uses uninsulated tools and passivating $NaClO_3$ electrolytes. The method shows advantages over other hole making techniques in terms of the resulting surface quality and process reliability. During machining with bare tools and passivating electrolytes, a transpassive condition would exist at the small frontal gap while passive conditions are obtained along the sides of the holes. Thus, the hole width would increase much slower than its length. Because of passivating electrolyte, good surface quality of the hole is expected. An improvement in process reliability is realized as tool insulation would be eliminated. Process details of ESD and STEM are reported in [1, 5, 6, 7, 8]

Kozak, Rajurkar and Balakrishna [9] have reported a mathematical model for determining relationship between the machining rate and working conditions (electrolyte flow velocity, jet length and voltage). They conducted the experiments using NaCl electrolyte on Inconel alloy material. The results of their study are shown in Fig 1.4. They found that machined hole diameter increases with increase in machining time. They reported that the aspect ratio depends on stand off distance and machining time.



(a) **Cost comparison**



(b) **Drilling capabilities compared**

Figure 1.3: (a) Costs comparison of various processes (b) Drilling capability comparison of various processes [1]

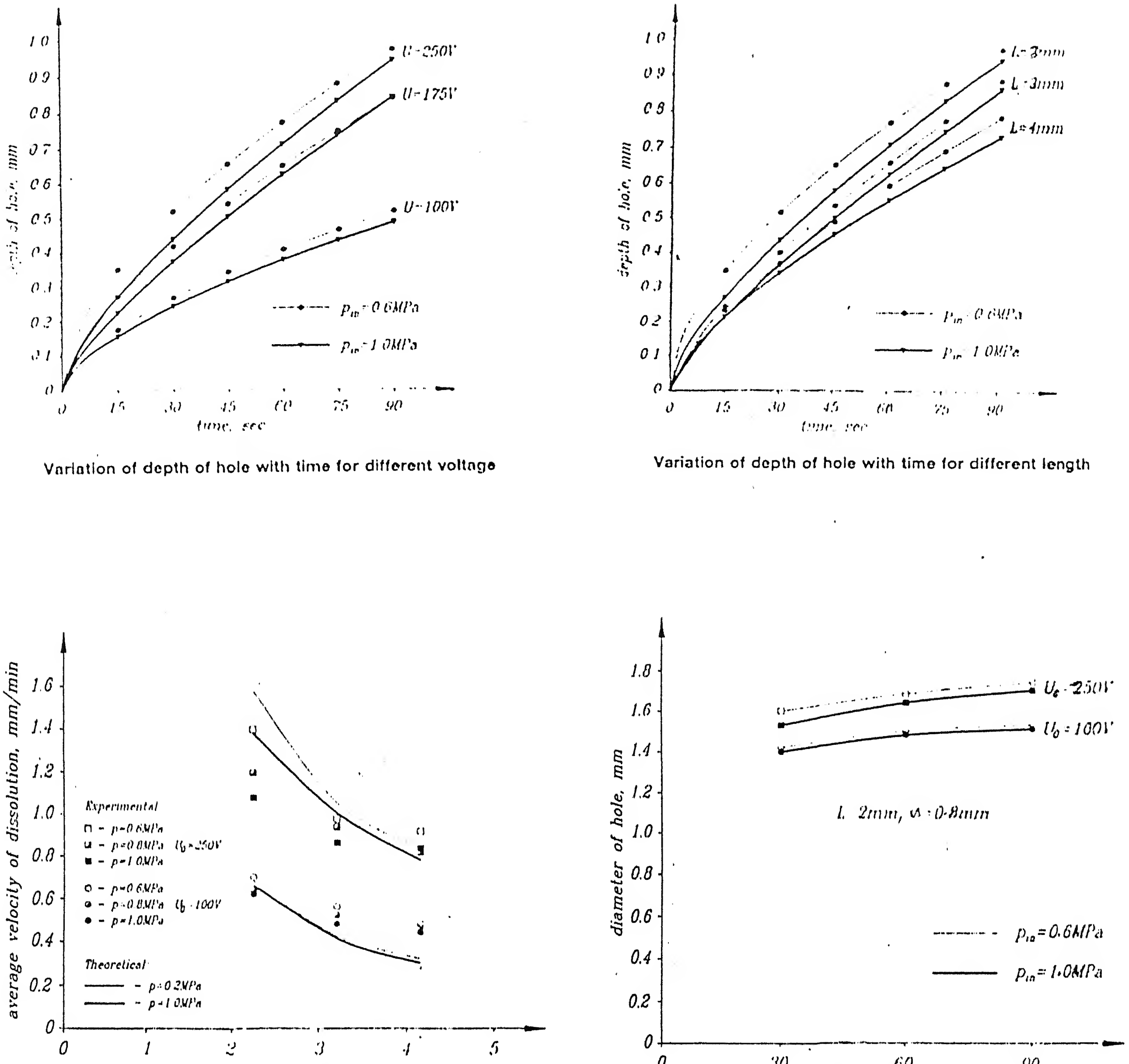


Figure 1.4: Parametric study during ECJM [9]

1.3 Objectives and scope of the present work

The literature survey reveals that in earlier research work on ESD, the parametric study has been done using salt electrolytes only. But drilling deep, small holes with salt electrolytes produces a large volume of sludge, which tends to clog the flow of electrolyte. An acidic electrolyte, however, dissolves the metal, and carries away as metal ions (Fig 1.1). So in the present work ESD is carried out using acidic electrolytes. The following are the main objectives of the present work.

- To design and fabricate an ESD setup to conduct drilling operations on electrically conducting and difficult to machine materials.
- To study the effect of process parameters (i.e applied voltage and electrolyte concentration) on material removal, machined hole depth, and hole geometry in ESD process.
- To find out the feasibility of using ESD process for drilling holes in super alloy materials (Inconel).

Chapter 2

Experimental setup and experimentation

Experiments have been conducted on an experimental electro-stream drilling machine, specially designed and fabricated for this purpose. The present chapter deals with the design, related instrumentation and experimentation.

The ESD machine has been designed keeping in view of the fundamental mechanism of the process. The basic requirements which are kept in mind while designing the setup are as follows:

- The material chosen for the equipment construction is resistant to corrosion due to acidic electrolyte.
- Proper sealing of the entire equipment to avoid the leakage of corrosive acid electrolyte.
- In ESD, high voltage and acid electrolyte are used, so proper electrical insulation is to be provided.

2.1 Parameter selection

From the machining data hand book [8] flow rates required for ESD process are 20-150 cm^3/min.

A flow rate of 120 cm^3/min is selected for further calculation of parameters i.e.

$$q = 120\, cm^3/min = 2\, cm^3/sec$$

Outlet diameter of the nozzle (d) used is

$$d = 0.5\, mm = 0.05\, cm$$

Cross sectional area of the nozzle outlet (A) is given by

$$A = (\frac{\pi}{4})\, d^2 = 1.963 \times 10^{-3}\, cm^2$$

For the selected parameters, flow velcity (v) is calculated as given below

$$v = \frac{q}{A} = 10.18\, m/sec$$

The pressure head (h) required for achieveing the calculated flow velcity is given by

$$h = \frac{v^2}{2g} = 5.28\, m = 0.52\, kgf/cm^2$$

a pump with 3 m head capacity is selected for supplying electrolyte during electro-stream drilling (ESD) process. Additional head due to gravity is obtained by placing the reservoir at an elevation. The combind head due to gravity and pump resulted in flowrate greater than theoritical value (i. e. 240 cc/min).

2.2 Electro-stream drilling machine

The drawing of the assembled ESD machine is shown in Fig 2.1. The ESD experimental setup can be divided into four distinct sub-assemblies. They are:

1. Work holding device,
2. Nozzle holding arrangement,
3. Electrolyte supplying system,
4. Electrical Power Supply

Basic components of a **work holding fixture** are

1. Work vice
2. Work table

Both are made up of perspex, as perspex is acid resistant material and it possess good electrical insulating properties. Work piece can be held in the work vice with the help of a tightening screw made of perspex. The work piece can be given horizontal feed manually, so that a hole can be drilled in a new position. This feed is achieved with the help of T-slot and slide mechanism in the work vice. The work vice is supported by the work table, which is fixed to the base of the machining chamber.

The Basic components of a nozzle and its holding arrangement are as follows:

1. Glass nozzle,
2. Perspex bush,
3. Lock nuts.

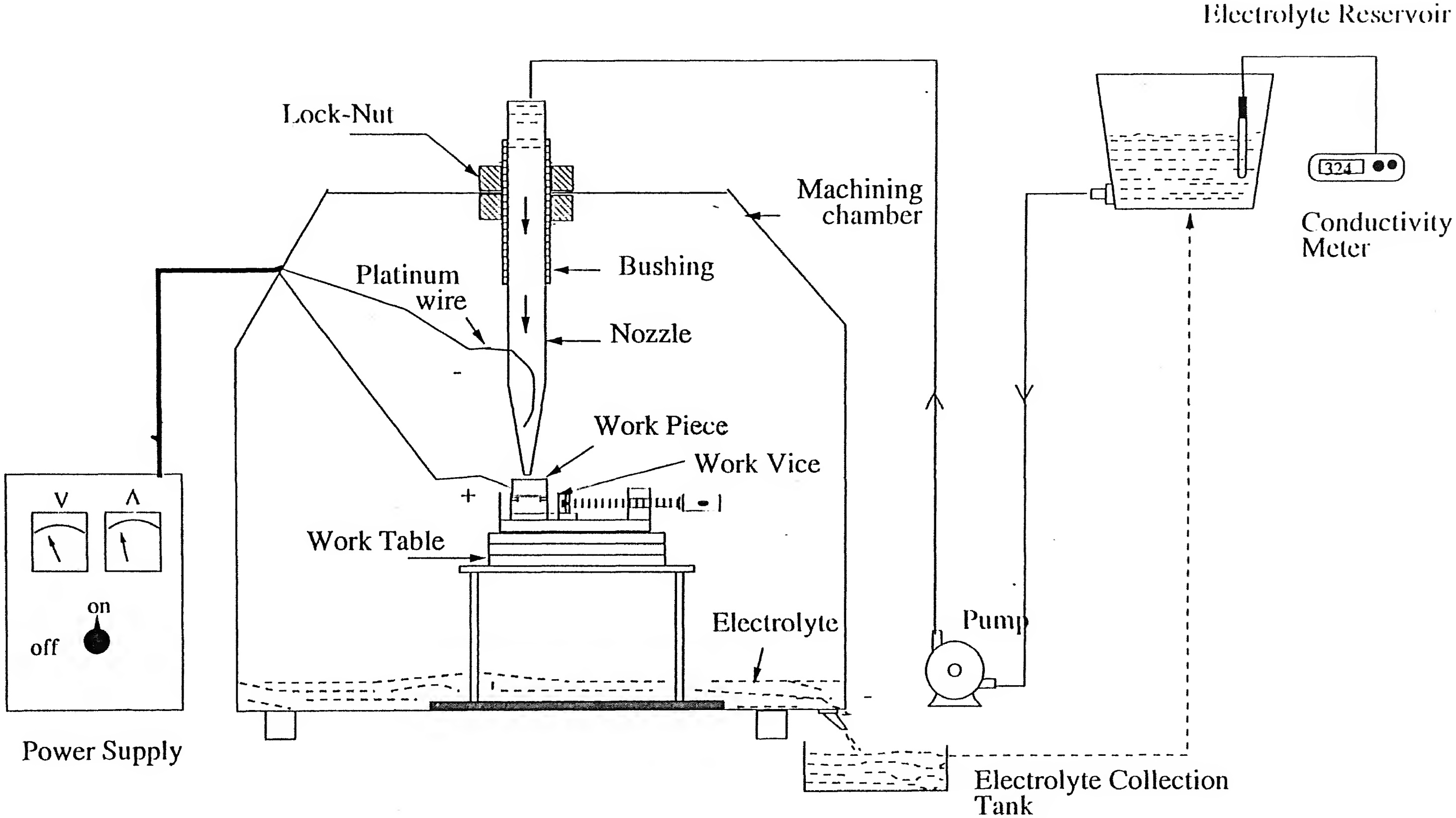


Figure 2.1: Electro-stream drilling machine

is shown in Table 2.2. The preliminary step is to set up the relationship between the scaled and actual values of parameters. The general equation showing their relationship is as follows:

$$scaled\,level = a + b \times actual\,level \tag{2.4}$$

In the design, scale the lowest and highest values of x as -1.414, and 1.414 for two x- variables. For voltage: $V_{min} = 50\,V$, and $V_{max} = 150\,V$. From equation 2.4,

$$1.414 = a + b \times 150 \tag{2.5}$$

$$-1.414 = a + b \times 50 \tag{2.6}$$

On solving eq 2.5 and eq 2.6 simultaneously, we get $a = -2.828$, and $b = 0.02828$. So

$$x_1 = -2.828 + 0.02828 \times V \tag{2.7}$$

Similarly for % concentration

$$x_2 = -2.121 + 0.1414 \times C \tag{2.8}$$

From eq 2.7and eq 2.8, voltage and concentration corresponding to the scaled levels -1, 0, 1 are determined. The complete conversion table is tabulated in Table 2.3. With the above conversion the experiments are conducted in the random order according to the plan given in Table 2.4.

Electrolyte	HCl
Inner dia of the nozzle	0.5 mm
Nozzle tip distance	1 mm
Wire tip distance	25 mm
Ambient Temperature	$34^{\circ}C$

Table 2.1: Test conditions

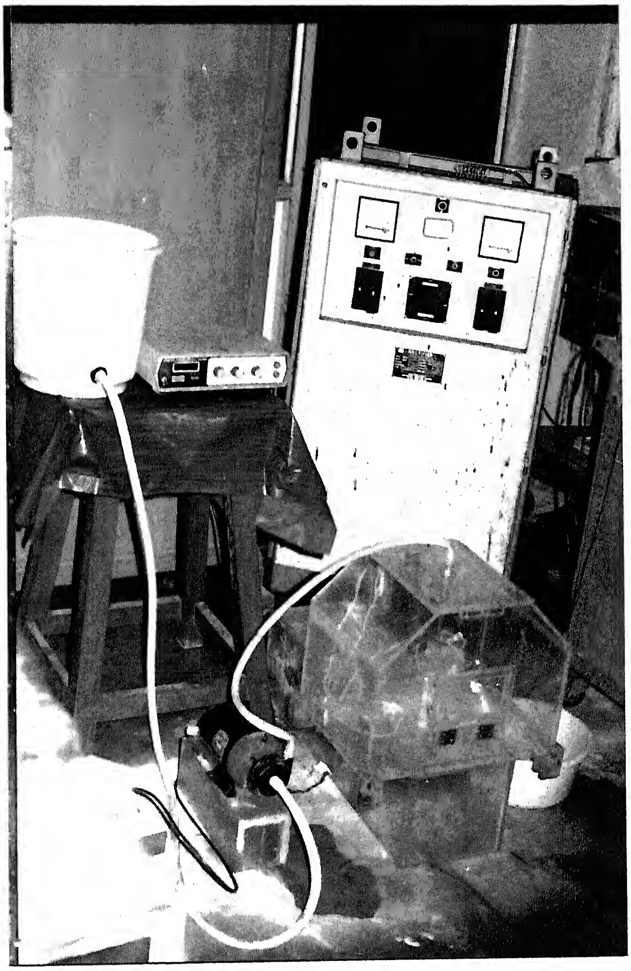


Figure 2.2: Photograph of ESD experimental setup

Inconel

Inconel is a super-alloy material of composition 16% chromium, 8% iron, and 76% nickel. This super-alloy has good high-temperature resistant properties, and is used in furnace mufflers, electronic components, heat exchanger tubing, nuclear reactors, springs and jet engine parts.

Electrolyte (HCl)

Experiments were conducted using hydro chloric acid (HCl) at different concentrations. Salt electrolytes have lesser electrical conductivity values. With the existing power supply (0-150 V) ESD machining with the salt electrolyte takes longer machining time. So acidic electrolyte (HCl) is used for machining.

2.7 Experimentation

Electrolyte of appropriate concentration is prepared and placed in the reservoir. The glass nozzle is gripped in the nozzle holder. The work piece is placed in the work vice and tightened with a screw. Initially the pump is switched on and electrolyte supply is ensured. Then the D.C. power supply is turned on to apply a potential difference across the platinum wire and work piece. The starting distance between the wire end and work is always kept constant by adjusting the nozzle prior to every experiment. Then machining of work material starts, and it is allowed to take place for 30 min. During machining, applied voltage, current drawn, and electrolyte conductivity, were measured. After 30 min, the pump is switched off. Workpiece is removed from the vice and thoroughly washed with water to remove any traces of electrolyte. Then the workpiece is dried under an electric bulb to completely remove any left-out traces of liquid from the machined blind hole. This is done before taking weight of the work piece after ESD. For conducting experiments at different electrolyte concentrations, the same procedure is repeated with a freshly prepared electrolyte. Some of the test conditions used during the experimentation are given in Table 2.1.

2.8 Material removal measurement

The weight of the workpiece is measured using the available electronic weight balance AFCOSET having a least count of 0.001g. The weight of the samples before and after machining is recorded. The difference in the two readings gives the amount of material removed.

2.9 Machined depth and machined diameter measurement

Split type of work pieces are employed for conducting experiments. Reason for using split type work pieces is to visualize the depth profile after machining.Two HSS tool bits of 5.6 mm $\times$ 5.6 mm cross section were soldered in lap-joint fashion as shown in Fig 2.3. After machining, the workpieces are parted off by removing the solder. Now the machined depth is measured using a shadow graph, Fig 2.4. At the two ends of the machined profile, readings of the micrometer were noted down. The difference in the reading gives the depth of the machined hole. The reading were taken at 20X magnification. The least count of the instrument is 0.001mm. The same procedure is adopted for measuring the diameter of the machined hole. Fig 2.5 refer to the measured diameter value.

2.10 Profile tracing of the diameter, and depth of the machined holes

It is very difficult to detect the exact profile of the machined hole with naked eye. So the machined hole profile is captured using the shadow graph at 20X magnification. The profiles are then traced on a transparency role. Deepest depth shown in Fig 2.5 is considered as the machined depth.

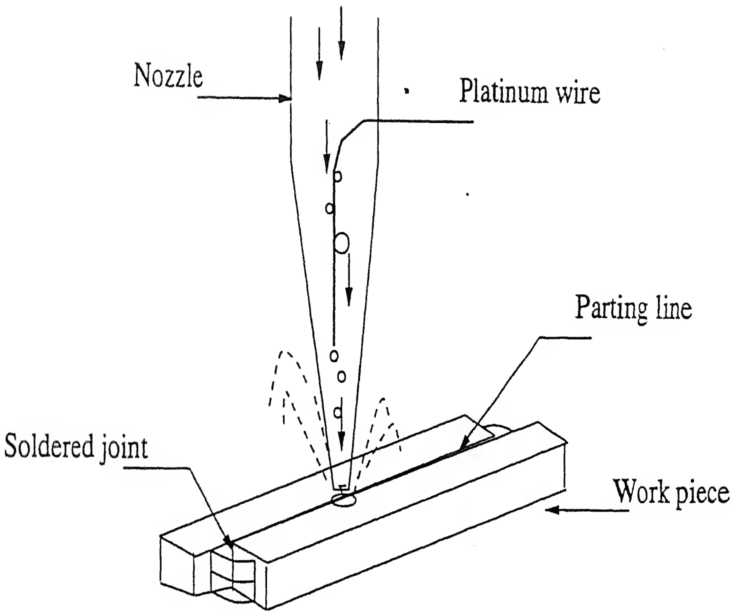


Figure 2.3: Schematic diagram of the soldered HSS workpiece

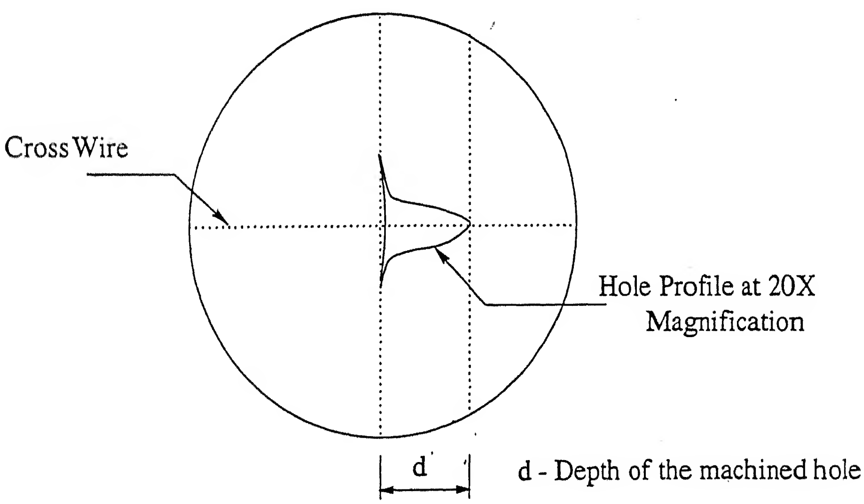


Figure 2.4: Machined depth measurement using shadow graph

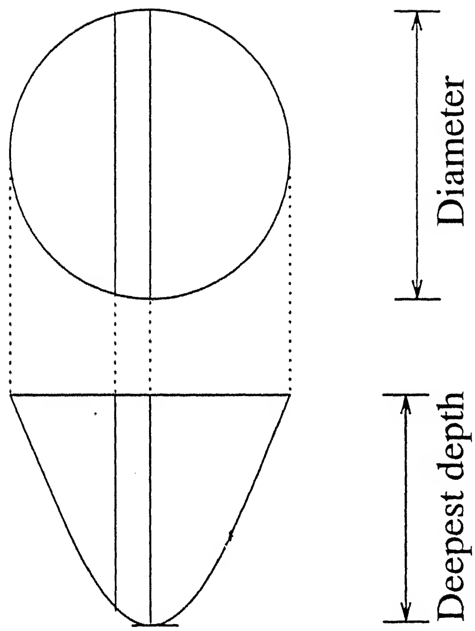


Figure 2.5: Schematic showing the deepest depth profile

2.11 Design of experiments

In design of experiments, the investigator organizes consecutive small series of trials, in each of which all the factors are simultaneously varied according to definite rules. The design of experiment is the procedure of selecting the number of trials and conditions for running them, essential and sufficient for solving a problem that has been set with the required precision. The following features are of great importance.

- striving to minimize the total number of trials,
- the simultaneous variation of all the variables determining the process according to special rules,
- the selection of a clear-cut strategy permitting the experimenter to make substantiated decisions after each series of trials of experiment.

Block diagram of the experimental system of study is shown in Fig 2.6.

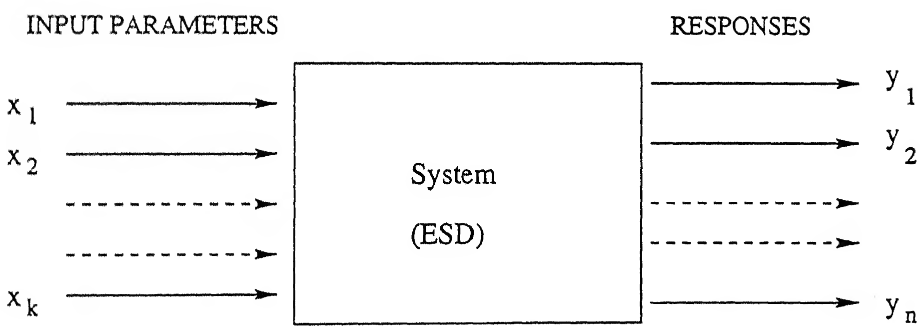


Figure 2.6: Block diagram of the experimental system of study

The arrows on the right show the numerical characteristic of the goals of investigation and they are called responses (yields). The variables that influence the behavior of the system responses are called factors, and they are input parameters shown on the left side in Fig 2.6.

The effect of independent parameters i.e voltage and electrolyte concentration on various responses considered is given below.

3.2 Material removal (or machined mass)

Following response surface equation is obtained from the experimental results (see Appendix) , for evaluating material removal y_{mr} by varying supply voltage (x_1) and electrolyte concentration (x_2). Here x_1 and x_2 refer to the coded level values.

$$y_{mr} = 156.037 + 52.21x_1 + 56.306x_2 + 1.906x_1^2 + 0.906x_2^2 + 18.25x_1x_2 \quad (3.1)$$

The effects of independent parameters affecting machined mass (material removal) in eq (3.1) is shown in Figs 3.5 and 3.6.

Fig 3.5 shows the effect of supply voltage on the material removal at different electrolyte concentrations. It is evident from the figure that the material removal increases with increase in supply voltage. Since, increase in voltage increases the machining current , this increase in current causes an increase in machined mass. Fig 3.5 also shows experimental points superimposed on the theoritical curves. It is seen from the figure that correlation between theoretical and experimental results is quite good.

Figure 3.6 shows the effect of electrolyte concentration on material removal at different voltages. It has been observed that material removal increases with increase in electrolyte concentration. This is due to an increase in concentration of electrolyte which leads to increase in its electrical conductivity. As a result more machining current will flow to the machining zone. This increase in current causes more material removal.

If all the input parameters represent quantitative variables then the yield (or response) can be represented as a function of the levels of the variables.

$$y = \phi(x_1, x_2, \ldots, x_k) \tag{2.1}$$

The function Φ is called the response surface. In the absence of knowledge of mathematical form of Φ, it can be approximated satisfactorily, within the experimental region, by a polynomial in the variables x. To obtain the idea of interactions and higher order effects, second order designs are preferred, Such quadratic type of designs are used when responses are not expected to be linear and the design is needed to yield estimates of the curvature aspects of each response. The general form of a quadratic (second degree) polynomial in two x-variables is as follows.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \tag{2.2}$$

Central composite rotatable designs are originated to fit second order response surfaces. To explain the concept of rotatability, let the point (0, 0, ... , 0) represent the center of the region in which y and x are under investigation. Let y be the estimated response at a point on the fitted second order surface as given by equation given below.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_i x_j \tag{2.3}$$

In rotatable designs, the standard error is the same for all the points that are at some distance P from the center of the region.

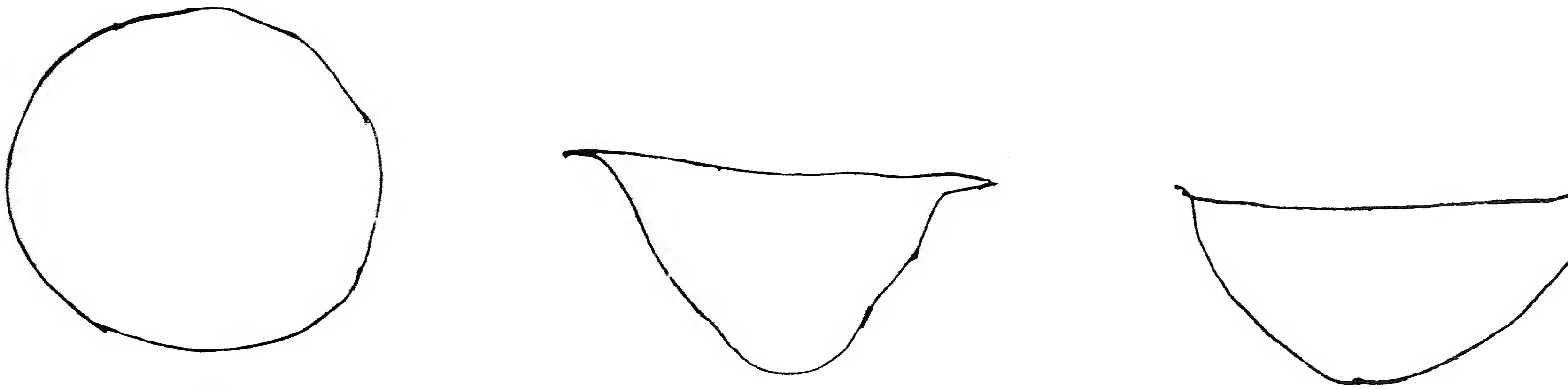
Design of experiments for ESD

To evaluate the effects of electrolyte concentration and voltage on material removal (machined mass) machined hole depth, and machined hole diameter (outer), central composite rotatable design was selected. The design for two x-variables

Experiment no	Design no	voltage (V)	concentration (%C)
1	1	65	8
2	2	135	8
3	4	135	22
4	3	65	22
5	8	100	25
6	7	100	5
7	5	50	15
8	6	150	15
9	9	100	15
10	10	100	15
11	11	100	15
12	12	100	15
13	13	100	15

Table 2.4: Complete conversion table for two factors

5

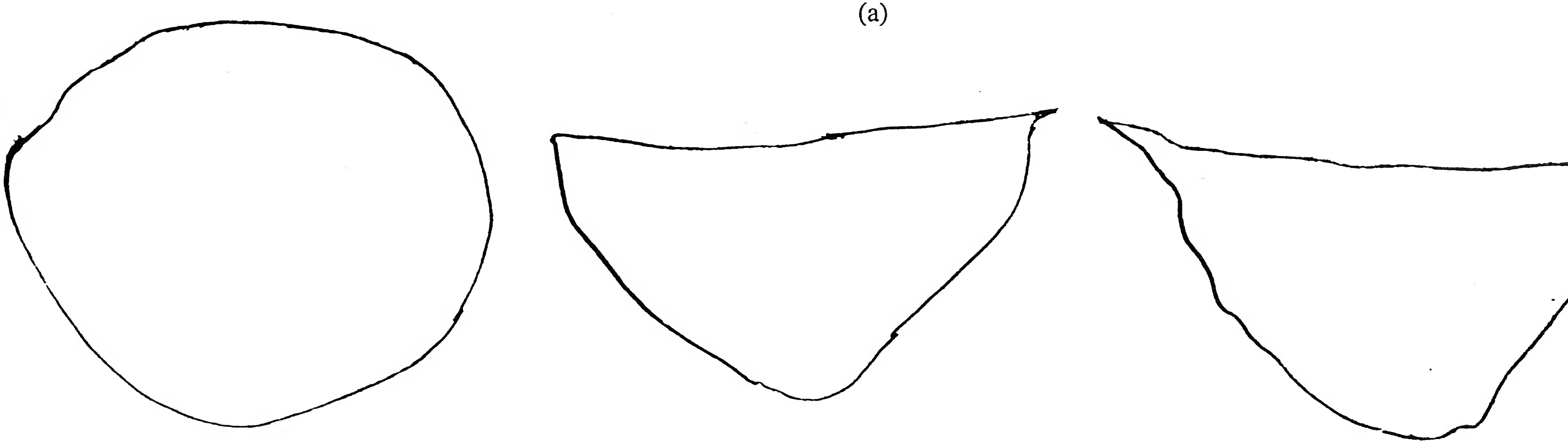


(i) (ii) (iii)

voltage = 50 V concentration = 15% machining time = 30 min

(a)

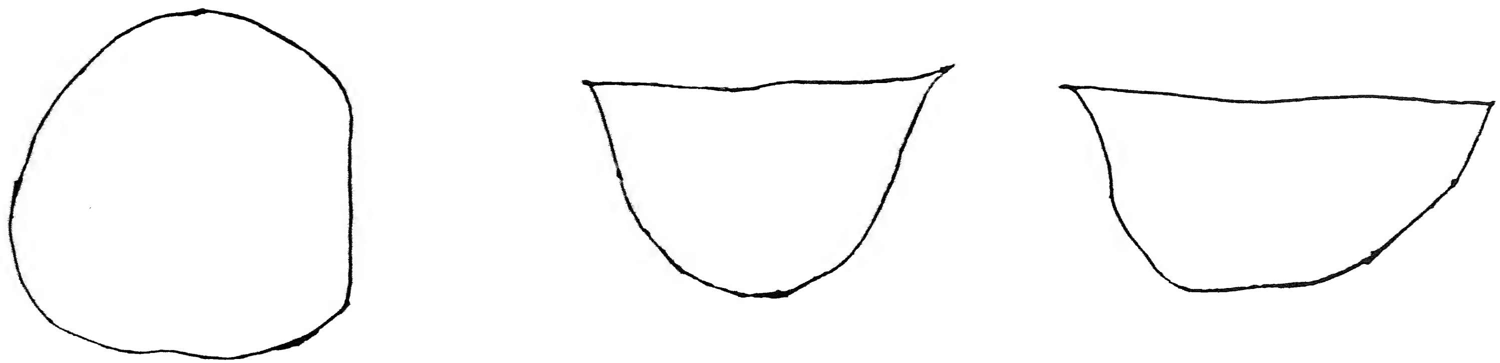
6



voltage = 150 V concentration = 15% machining time = 30 min

Fig 3.1 (b)

7

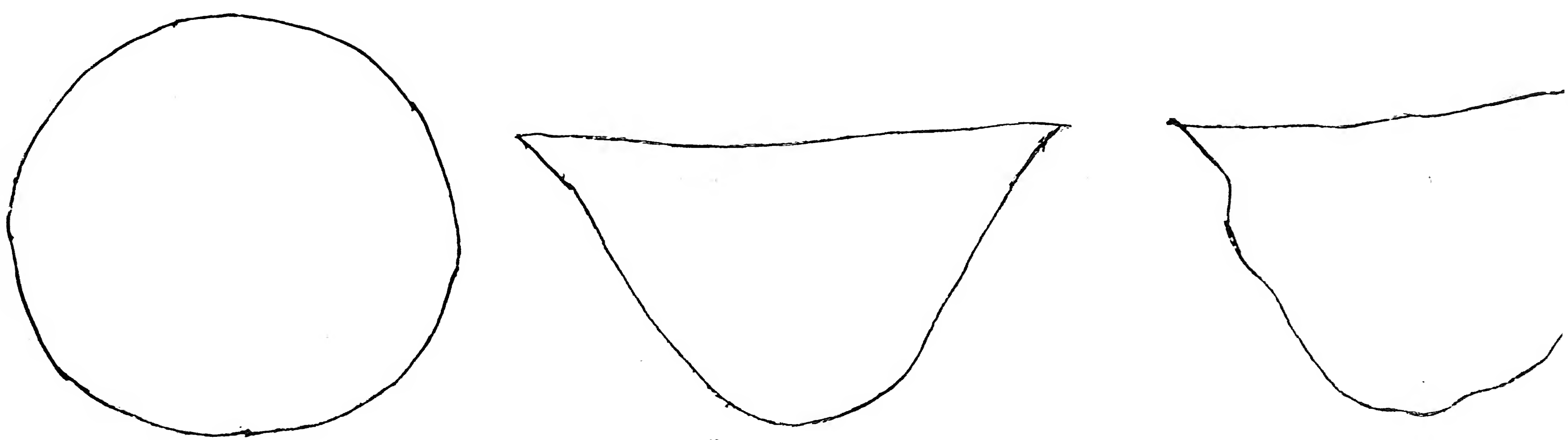


(i) (ii) (iii)

voltage = 100 V concentration = 5% machining time = 30 min

(c)

8



(i) (ii) (iii)

voltage = 100 V concentration = 25% machining time = 30 min

Fig 3.1 (d)

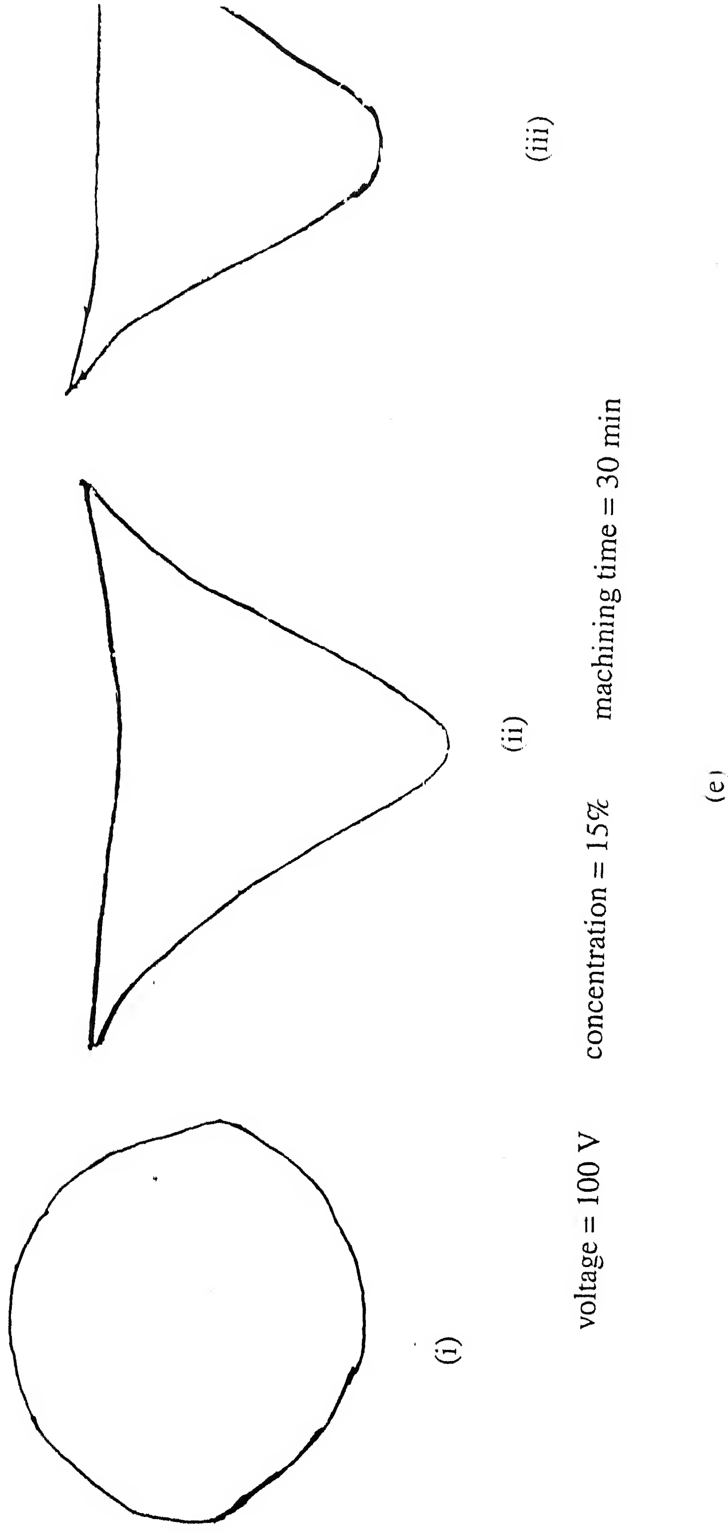
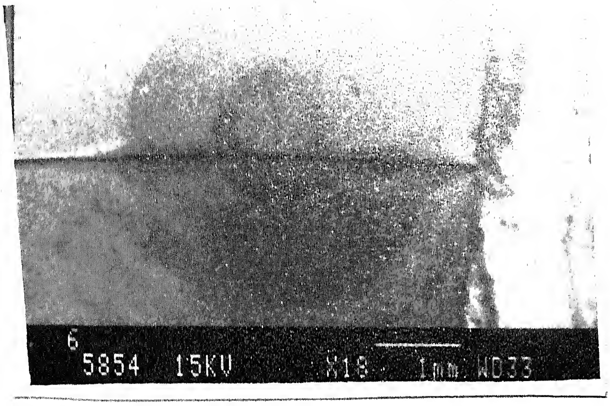
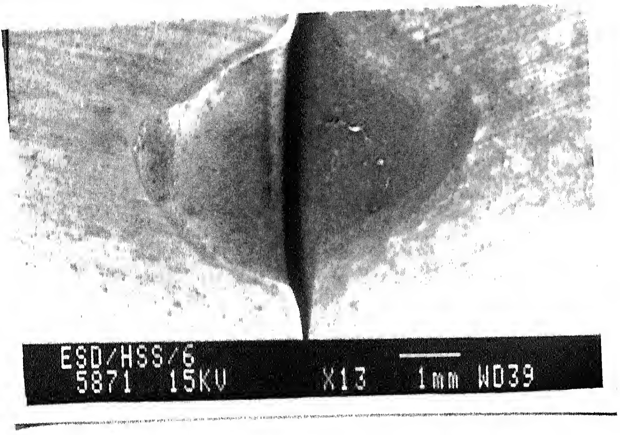


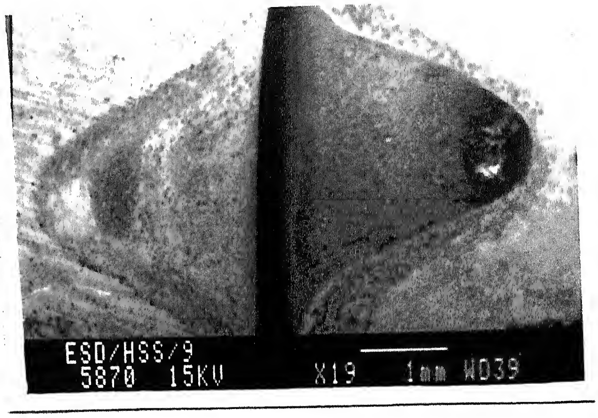
Figure 3.1: Shadow graphs (a-e) of the machined holes under different machining conditions. (i) top surface diameter, (ii) and (iii) variation in machined depth in two splitted parts of the work piece. (a-b) effect of voltage, (c-e) effect of concentration.



(a) Blind hole in HSS in 30 min at 150 V and 15% electrolte concentration



Depth profile view of hole machined in HSS during 30 min machining at 150 V and 15% electrolyte concentration



(c) Depth profile view of hole machined in HSS during 30 min machining at 100 V and 15% concentration of electrolyte

Figure 3.3: SEM photographs of the ESD machined holes

s.no	voltage (V)	concentration (%C)	taper angle	inner dia (mm)
1	65	8	42.79°	0.7
2	135	8	33.69°	0.75
3	65	22	34.33°	0.65
4	135	22	39.52°	0.95
5	50	15	28.61°	0.65
6	150	15	31.18°	1.2
7	100	5	25.46°	1.1
8	100	25	38.08°	1.2
9	100	15	32.0°	0.4

Table 3.1: Taper angles of ESD machined holes at different operating conditions

Experiments are planned according to central composite rotatable design for two input parameters. According to the plan 13 experiments are conducted. Out of which 5 experiments are conducted under the same operating conditions. Reproducibility of these experiments is shown in the Fig 3.4.

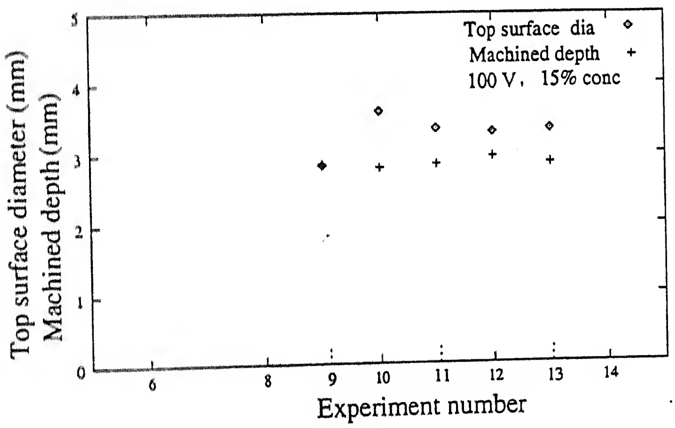
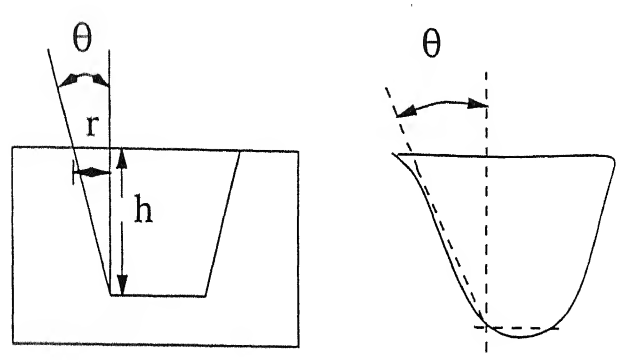


Figure 3.4: Reproducibility plot

ESD drilled holes have taper. Fig 3.2 shows the representation used for indicating taper.



(a) (b)

Figure 3.2: (a) Representation of taperness (b) taper angle measurement for actual case

Taper angle is calculated from the hole profile, using the formula given below.

$$\theta = tan^{-1}(\frac{r}{h})$$

where, r and h are shown in Fig 3.2. Taper angles of the holes drilled by ESD process for different machining conditions using HSS as work material are shown in Table 3.1. Values of taper angles are calculated from the profiles of holes in Fig 3.1. The hole with good quality is obtained for 100 V, and 5% concentration conditions, i.e the taper angle (hole taper) is found to be min at this conditions (Table 3.1). For the experiments conducted max machined diameter is obtained at 150 V and 15% concentration, and the max machined depth is obtained for 100 V and 15% concentration conditions.

SEM photographs of blind holes in HSS shown in Fig 3.3 (a), and depth profile of machined holes in HSS at different operating conditions are shown in Fig 3.3 (b) and (c).

4.2 Scope for the future work

- A system can be developed having very fine nozzle which can penetrate with jet inside the hole and higher aspect ratios could be obtained.

- Different electrolytes could be tried. Based on material to be machined electrolyte is to be selected. some of the materials, and electrolytes appropriate for their machining is as follows. HCl is used for machining Aluminium, Inconel, Ti - 6Al - 4v , SEL15. H_2So_4 can be used to machine carbon steel, stainless steel, udimet, rene, Hast alloy, Heynes alloy. Passivating electrolytes like $NaClo_3$ can be helpful in achieving good dimensional accuracy of the machined hole.

- Pulsed power supply could be used for improving the process performance. By employing pulsed power supply, machining takes place only during pulse on time, and during off time no reaction takes place. During this period the fresh incoming electrolyte scavenges the reaction products and build up of concentration of ions in the machining zone. This aspect reduces the resistance to current flow and may help in improving process performance.

- Present developed system can be further improved in design to increase its flexibilities for various critical parameters (e.g Increase in power supply voltage limit).

- STEM process can be further explored to achieve higher aspect ratios. Fig 4.1 shows the schematic diagram of the STEM process.

3.3 Machined hole diameter

The response surface equation obtained from experimental results, for evaluating machined hole diameter y_d by varying supply voltage and electrolyte concentration is as given below:

$$y_d = 2.833 + 0.631x_1 + 0.722x_2 + 0.146x_1^2 + 0.052x_2^2 + 0.027x_1x_2 \qquad (3.2)$$

From eq (3.2) parametric analysis has been conducted, and the effects of different parameters on machined hole diameter are shown in Figs 3.7 and 3.8.

The effect of voltage on the diameter of the machined hole at different concentrations of the electrolyte is shown in Figure 3.7. It is evident from the figure that the top surface diameter of the machined hole increases with increase in supply voltage. This increase in diameter is attributed partly to the stray current effect and partly to the fact that this portion of the work piece is subjected for maximum period of time to electro-chemical dissolution throughout the machining operation [2]. The magnitude of stray current will be more at higher voltage which leads to more widening of the top surface diameter of the hole .

Fig 3.8 shows the effect of electrolyte concentration on top surface diameter of the machined hole at various voltages. The diameter is found to increase with increase in electrolyte concentration. This increase is attributed to stray current effect (i.e. side wise current flow). The magnitude of current will be more at higher concentration .

3.4 Machined hole depth

Following response surface equation is obtained from the experimental results for evaluating machined hole depth y_h by varying supply voltage and concentration of electrolyte.

$$y_h = 2.867 + 0.347x_1 + 0.454x_2 - 0.238x_1^2 - 0.528x_2^2 - 0.1227x_1x_2 \quad (3.3)$$

From eq (3.3), parametric analysis has been conducted, and the effects of parameters on machined hole depth is discussed.

The variation in depth of the machined hole with voltage at different concentrations of the electrolyte is shown in Fig 3.9. With increase in voltage, machined depth initially increases reaches a maximum value and then decreases. The reason for this behavior seems to be the effect of black deposit formation in the machining zone during ESD of HSS. At lower voltages the deposit formation is observed to be less, which is effectively flushed out by the flow of electrolyte, that results in an initial increase in the machined depth with voltage. At higher voltages the hole drilled in HSS,after machining is covered a thick, tenacious black film. This thick black film is similar to the results discussed in references [12, 13]. They reported that the black film formation induces partial passivation. They also reported that the presence of electro-chemically inert carbon on the machined surface reduces metal dissolution reaction and result in another reaction. Their tests with different amount of carbon in the steels emphasize that carbon itself, or its effect on the metallurgical structure plays an important role in inducing the passivation. During ESD of HSS also the thick black passivating film formation is supposed to be the cause of reduction in material removal in z-axis direction.

Fig 3.10 shows the effect of concentration of electrolyte on machined depth at different voltages. With increase in electrolyte concentration, the machined depth increases initially, reaches to a maximum and then decreases. The explanation for decrease in machined hole depth with concentration after maxima seems to be same as explained in previous paragraph (i.e. Partial passivation caused by the formation of thick black film at higher electrolyte concentrations).

3.5 Experiments on Inconel

ESD is conducted on a 2mm thick 10mm dia Inconel work piece at 100 V, and 15% concentration for a period of 15min (At this condition max machined depth is obtained for HSS). SEM photograph of the machined hole is shown in Fig 3.11.

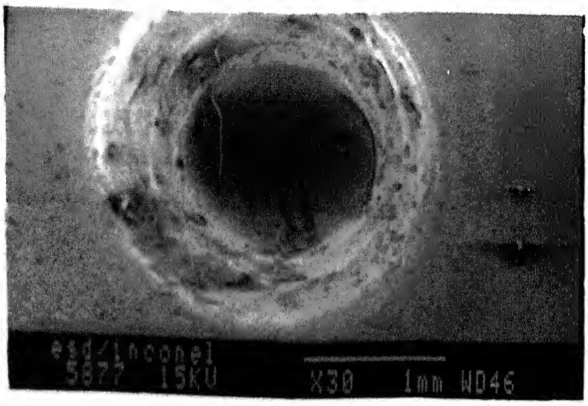


Figure 3.11: SEM photograph of blind hole machined in Inconel

As the experiments carried out on HSS with ESD process resulted in holes with lesser machined depth values even after applying voltages up to 150 V. So, another approach is tried out using the injection needle (18 gauge) as the tool instead of electrolyte stream.

Few trial experiments are carried out on (5 mm thick, 10 mm diameter) inconel work pieces supplied by BHEL, using injection needle as cathode (tool). The experiments are carried out at 20% electrolyte concentration and 25 V. During experimentation fine feed is given to the tool manually. The observations made during machining of inconel alloy are as follows:

- At lesser voltages machining of inconel is possible with needle as cathode. This may be due to lower resistance to current flow, because of small inter-electrode gap.
- In the absence of gap detecting sensor short circuiting is the problem frequently observed. This may be due to two reasons. 1. The tool feed rate is faster than the rate of material removal. 2. Contact between the tool and the side walls of the machined hole.

- The major problem observed is clogging of the tool by deposition taking place at cathode. This problem occured quite often and at this point continuous arcing was observed.

- To avoid the problem of tool clogging due deposition reaction. Polarity is reversed for a short period of time as a result the deposit is removed and electrolyte flow is restored. This reversing of polarity is to be done periodically to allow continuous flow of electrolyte. It was also observed that applying the reverse polarity also resulted in tool erosion.

- Another critical problem observed is corrosion of tool material. So instead of normal injection needles, using Titanium, Gold, or Platinum tubing may be effective. As these metals possesses good acid resistant properties and good electrical conductivity.

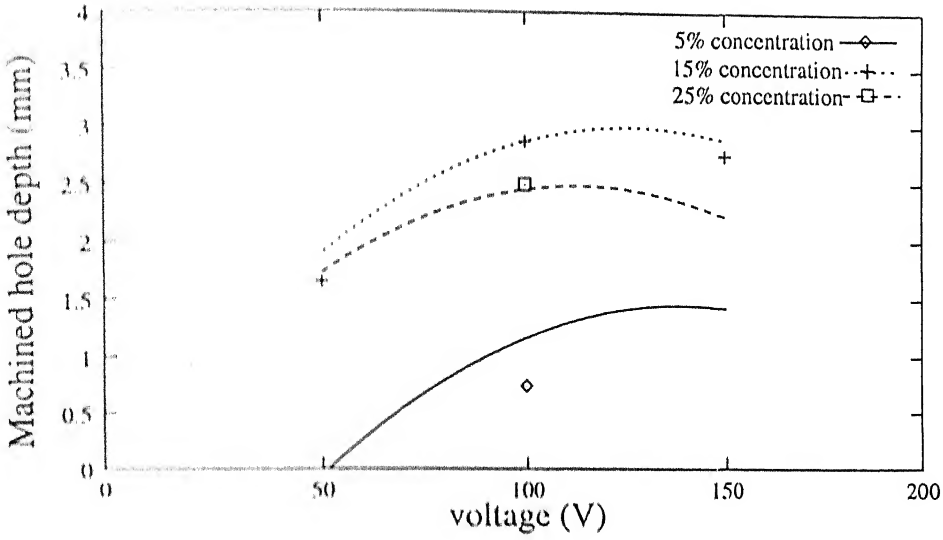


Figure 3.9: Effect of voltage on machined hole depth at different electrolyte concentrations

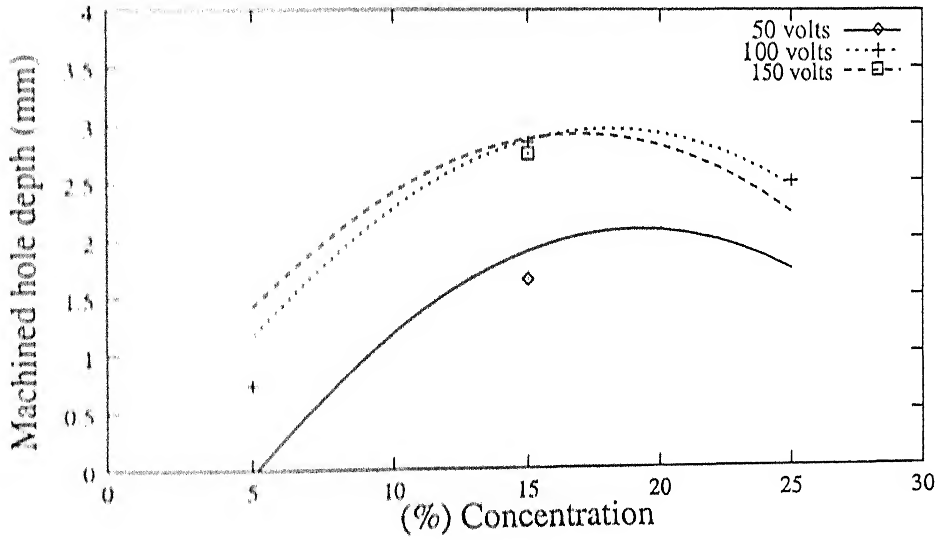


Figure 3.10: Effect of electrolyte concentration on machined hole depth at different voltages

Chapter 4

Conclusions and scope for the future work

4.1 conclusions

1. The study conducted has shown that the ESD process is feasible and advantageous in machining small diameter hole drilling in HSS and Inconel.

2. Performed experiments demonstrated feasibility of the use of HCl as electrolyte in place of normally used NaCl.

3. Parametric study shows that both material removal and machined hole diameter increase with increase in voltage and electrolyte concentration similar to normal ECM but in different machining conditions.

4. There exists optimum values for voltage and concentration at which machined depth is maximum.

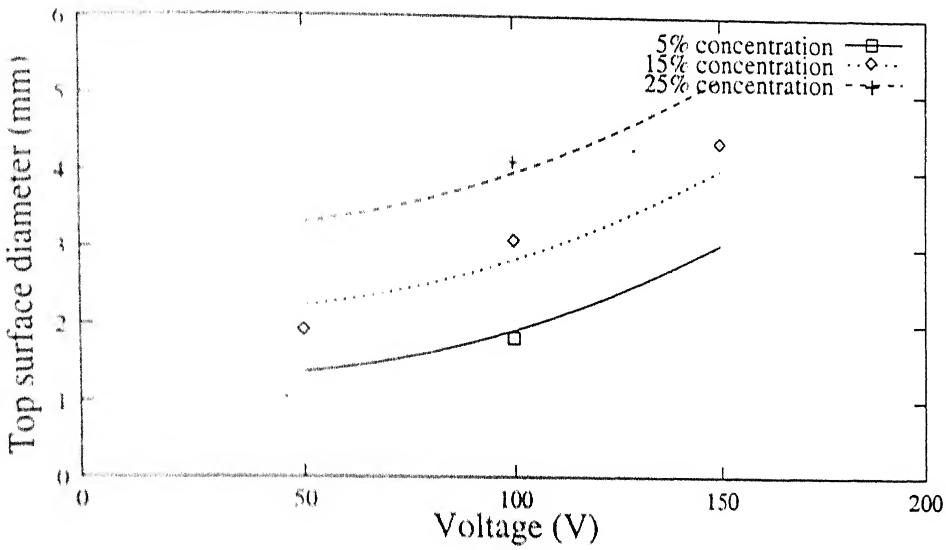


Figure 3.7: Effect of voltage on top surface diameter of the mahined hole at different electrolyte concentrations

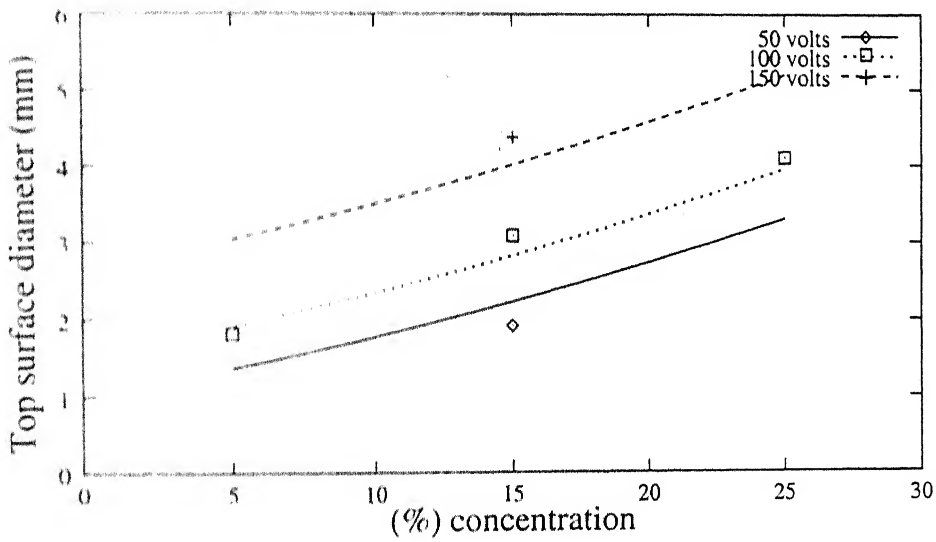


Figure 3.8: Effect of electrolyte concentration on machined hole diameter at different voltages

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10. John, F.W., "Practice and Theory of electro-chemical machining", John Willey & Sons, Inc., New York, 1972.

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13. McGeough, J.A.,"Some effects of carbon content on the efficiency of electro-chemically machined carbon steels and cast iron", Int. J. Prod. Res., Vol. 9, No. 2, pp 311-316, 1971.

sr. no.	voltage (v)	conc. (%w/v)	current (A)	machined mass (mg)	machined dia. (mm)	machined depth (mm)	conductivity time (min)	(mho) k	pH
1	65	8	0.0804	77	2.005	1.571	10	241	0.3
							20	235	
							30	250	0.26
2	135	8	0.176	144	2.743	2.432	10	256	
							20	258	0.02
							30	260	
3	65	22	0.196	142	3.227	2.397	10	648	0.56
							20	646	0.39
							30	646	
4	135	22	0.407	282	4.074	2.767	10	650	
							20	650	
							30	650	
5	50	15	0.121	83	1.923	1.653	10	284	
							20	249	
							30	253	
6	150	15	0.358	232	4.374	2.747	10	152	
							20	153	
							30	153	
7	100	5	0.089	68	1.818	0.744	10	152	
							20	152	
							30	152	
8	100	25	0.363	243	4.103	2.494	10	780	
							20		
							30		
9	100	15	0.235	156	2.841	2.861	10	286	
							20		
							30		
10	100	15	0.236	170	3.605	2.804	10		
							20		
							30		
11	100	15	0.226	136	3.357	2.852	10		
							20		
							30		
12	100	15	0.223	137	3.304	2.957	10		
							20		
							30		
13	100	15	0.222	144	3.347	2.863	10		
							20		
							30		

Table 4.2: Experimental values obtained during ESD of high speed steel (HSS)

ECM	Electro chemical machining
LBM	Laser beam machining
EDM	Electro discharge machining
EBM	Electron beam machining
PAM	Plasma arc machining
STEM	Shaped tube electrolytic machining
ESD	Electro stream drilling
q	Flow rate
d	Outlet diameter of the nozzle
A	Cross sectional area of the nozzle outlet
v	Flow velocity
h	pressure head
y_{mr}	Machined mass
y_d	Machined hole diameter
y_h	Machined hole depth

In ESD, glass nozzle of approximately 0.5 mm outlet diameter is used to produce a jet of electrolyte. It is drawn from corning glass, which possesses good strength and is inert to chemicals. The nozzle is also heat treated to impart additional strength to sustain the pressure of incoming acidic electrolyte.

A platinum wire inserted in the nozzle acts as cathode. The perspex bush firmly grips the nozzle, and the lock nuts are tightened over the bush on either side of the top cover plate of the chamber. This nozzle holding arrangement provides a movement of 10 mm on either side.

2.3 Electrolyte supply system

The Basic requirements kept in mind while designing electrolyte flow system are:

- Usage of acidic corrosion resistant materials, instrumentation and piping in the flow path.
- Proper sealing of the system, especially at junctions, like pump manifolds to avoid the leakage of the electrolyte. So the system is made leak proof.
- Facility to collect spent electrolyte.

Basic components of an electrolyte supply system are as follows :

Reservoir

From which the acid electrolyte can be drawn into the system, and to which the used electrolyte is returned. In the present system a plastic tank of 25 liters capacity was made as a reservoir

Pump

A pump is required to force the electrolyte from the reservoir into the machining zone. The casing of the pump is made of gunmetal, which is partially anti

2.5 Machining Chamber

The chamber housing is made of perspex (Fig 2.1) of dimensions 400 mm $\times$ 250 mm $\times$300 mm. The machining chamber houses the work holding device, and nozzle holding arrangement. Basic requirements taken into consideration while designing the machining chamber are as follows.

1. Chamber is provided with a slope at the top to drop down the sprinkled liquid electrolyte to the bottom. This avoids flowing of liquid on the chamber walls and thereby improves the process visibility to the user.

2. The chamber is provided with a detachable top cover plate for making adjustments from the top whenever necessary. This aspect helps in easy adjustments, and improves flexibility of the system.

3. The chamber is provided with an outlet at the bottom to facilitate used electrolyte disposal.

4. The chamber is provided with 12 V D.C. exhaust fan to drive away the hazardous fumes released during machining.

2.6 Work Material And Electrolyte

HSS and Inconel have been used as the work materials, because of their difficulty in machining by conventional machining methods.

High speed steel (HSS)

This is also called tool steel. HSS is used as cutting tool material for turning, milling, shaping , planing , broaching etc. It retains high hardness while cutting metal at very high speeds. HSS used during the present work is an alloy of 18% tungsten, 4% chromium, 1% vanadium, 0.75% carbon and remaining iron. It softens above 600°C.

Chapter 3

Results and discussion

In this chapter profiles of the holes drilled by ESD process have been studied. The shadow graphs of the depth and diametral profiles of the holes at different machining conditions are presented and discussed. Geometrical parameters such as taper angle of the holes are presented. Effect of applied voltage and electrolyte concentration on machined mass (or material removal), machined hole outer diameter (top surface diameter), and machined depth are presented and discussed.

3.1 Machined hole profile

The diameter, and depth profiles traced using the shadow graphs with 20 X magnification at different machining conditions are shown in Fig 3.1 . The figure shows that the machined holes have conical profile i.e. the hole diameter gradually decreases from top to bottom of the hole. The reason for an increase in diameter of the hole at the top surface is partly attributed to the stray current effect and partly due to the fact that this portion of the workpiece is subjected to electro-chemical dissolution throughout the period of drilling. At the bottom of the hole due to large gap, the current density would decrease, with the result that comparatively lower overcut (low mrr) takes place and hence the profile gets twisted towards the center. Asymmetry is observed in opposite faces of hole profiles, this may be due location of hole center not exactly along the parting line